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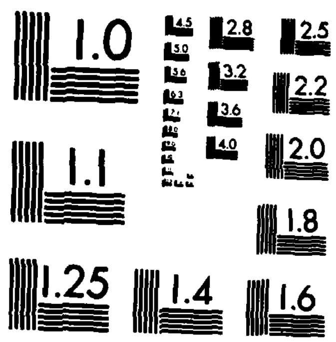
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THESIS

EXAMINATION OF THE SONAR DETECTION MODELS
USED BY THE
NAVAL WAR COLLEGE GAMING SYSTEM

by

David Martin Cashbaugh

June 1983

Thesis Advisor: N. Forrest

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Examination of the Sonar Detection Models Used By the Naval War College Gaming System

by

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This thesis describes an evaluation of the active and passive acoustic detection modules of the Naval War College Gaming System (NWCGS) that has been installed at the Naval War College in Newport, Rhode Island. The specific intent of the evaluation is to verify that the model is theoretically sound. This evaluation compares the NWCGS model to other existing acoustic detection models. Recommendations for improvement to the model are also presented.

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I. THE NAVAL WAR COLLEGE GAMING SYSTEM MODEL

The detection modules used by the Naval War College Gaming System (NWCGS) simulate the acoustic detection process using the generalized expected value sonar equations developed during the Second World War. Signal Excess, the difference between the existing signal-to-noise ratio and that required to achieve a specified level of performance, is the fundamental parameter that determines whether or not a detection has occurred. In the NWCGS, the value of signal excess is determined by the following two equations:

$$SE = SL - TL + DI - NL - DT \qquad (1)$$

when modeling mpassive sonar detections, and

$$SE = SL - 2TL + TS - (NL + DT) \qquad (2)$$

when modeling active sonar detections.

The parameters referenced by equations (1) and (2) are defined as follows:

SE - Signal Excess

SL - The source level of the target as measured one yard from the acoustic center of the effective sound source

DI - The directivity index of the hydrophone

TL - The one-way transmission loss from the target to detector

NL - The non-target noise in the immediate area of the receiver

TS - The target strength as measured one yard from the acoustic center of the target

DT - The detection threshold. This is the signal-to-noise ratio (in decibels) required to achieve a specified probability of detection at a specified probability of false alarm

A more complete description of these parameters is presented in Appendix A. The discussion which follows describes the methods used in the Naval War College Gaming System to determine appropriate values for the parameters of equations (1) and (2).

A. METHOD

The primary method of data retrieval used by the NWCG system is the multi-parameter "look-up" table. A look-up table can be described as an array having indices that reference its entries. The entries in the look-up table describing acoustic transmission loss are transmission loss values for different ranges and different environmental conditions. It is an example of a two-dimensional look-up table. The first index of the table identifies the environmental conditions assigned to the area of the game. The second index identifies the distance traveled by sound waves from the target to the detector. The advantage of a look-up table is its ability to make use of calculations done in advance. By using a look-up table, the amount of computations done during the course of a game is reduced, and the maximum

possible game speed is increased. The benefits of a faster game are not without some cost. The expense of using a look-up table is the requirement for additional memory and associated hardware used to store the tables. Because a look-up table is a discrete approximation of a continuous process, the accuracy of any signal excess model that utilizes a look-up table is limited by the resolution of the tables being used. In the transmission loss look-up table example, the look-up table index describing target-to-sensor range has a resolution of 1000 yards. This means that ranges are rounded to the nearest 1000 yards before entering the transmission loss look-up table. Increasing the table range resolution from 1000 to 500 yards requires twice the memory currently required. The presentation that follows examines each parameter of equations (1) and (2), and the tables used by the NWCGS to determine values for each.

B. TRANSMISSION LOSS

Transmission loss (described in the NWCGS documentation as propagation loss PL) is determined through a two-parameter look-up table. The first parameter determines the environmental conditions in the area of the game. All players are assumed to be contained in a single environmental area, and the sound velocity profile is assumed to be the same throughout all parts of that area. The second parameter of the table is range from target to source (rounded to the nearest 1000

yards). For a given environmental area, transmission loss becomes a function only of range. Such a table can adequately account for acoustic spreading losses, however as described in Appendix A, absorption and other forms of transmission loss depend upon other factors in addition to range.

1. Direct Path Mode

When both the target and the searcher are in the mixed surface layer, transmission loss is primarily a function of range r from target to searcher, target depth D_t, and layer depth D_l. Sound spreads spherically until it fills the layer (at transition range r_t), and then spreads cylindrically. Acoustic waves can be scattered at the surface, or may leak out of the bottom of the mixed layer. The total loss due to surface reflections is equal to the loss per surface reflection multiplied by the number of surface reflections that occur between target and searcher. The number of reflections occurring is simply the distance between target and detector divided by the distance between reflections. The complete expression for direct path transmission loss (when both target and searcher are within the mixed surface layer) is given by the expression [Ref. 1]:

$$TL = 10 \log r_t + 10 \log r + ar + br/r_r \qquad (3)$$

where:

r = horizontal range from target to searcher

r_t = 115 sqrt(D^2/(D_t-D_l)

a = absorption coefficient

b = loss (dB)/reflection = 0.63*freq*$(1.4)^{(\text{sea state})}$

r_r = 919 sqrt(D_l)

The transmission loss look-up table used by the NWCGS model describes only losses due to cylindrical spreading. Values obtained from such a table can only be used to determine values for the first two terms of equation (3). The table does not depend upon the environmental area of the ocean (since cylindrical spreading is the same in all environments); and it can be reduced to a one-dimensional table dependent only upon the target-to-searcher range. The curve of Figure 1 shows how cylindrical spreading loss varies as a function of range. This plot shows that a look-up table having a 1000 yard resolution can be responsible for table round-off errors that exceed 4 dB. In some cases, an error of this magnitude may not be acceptable.

The two transmission loss terms of equation (3) that cannot be described by the two-dimensional look-up table used in the NWCGS are the losses due to absorption and the losses which occur as a result of scattering of acoustic energy at the sea surface or "leakage" of energy out of the bottom of the layer. Scattering losses are functions of range, sea state and signal frequency. A three-dimensional look-up table that would be necessary to describe scattering

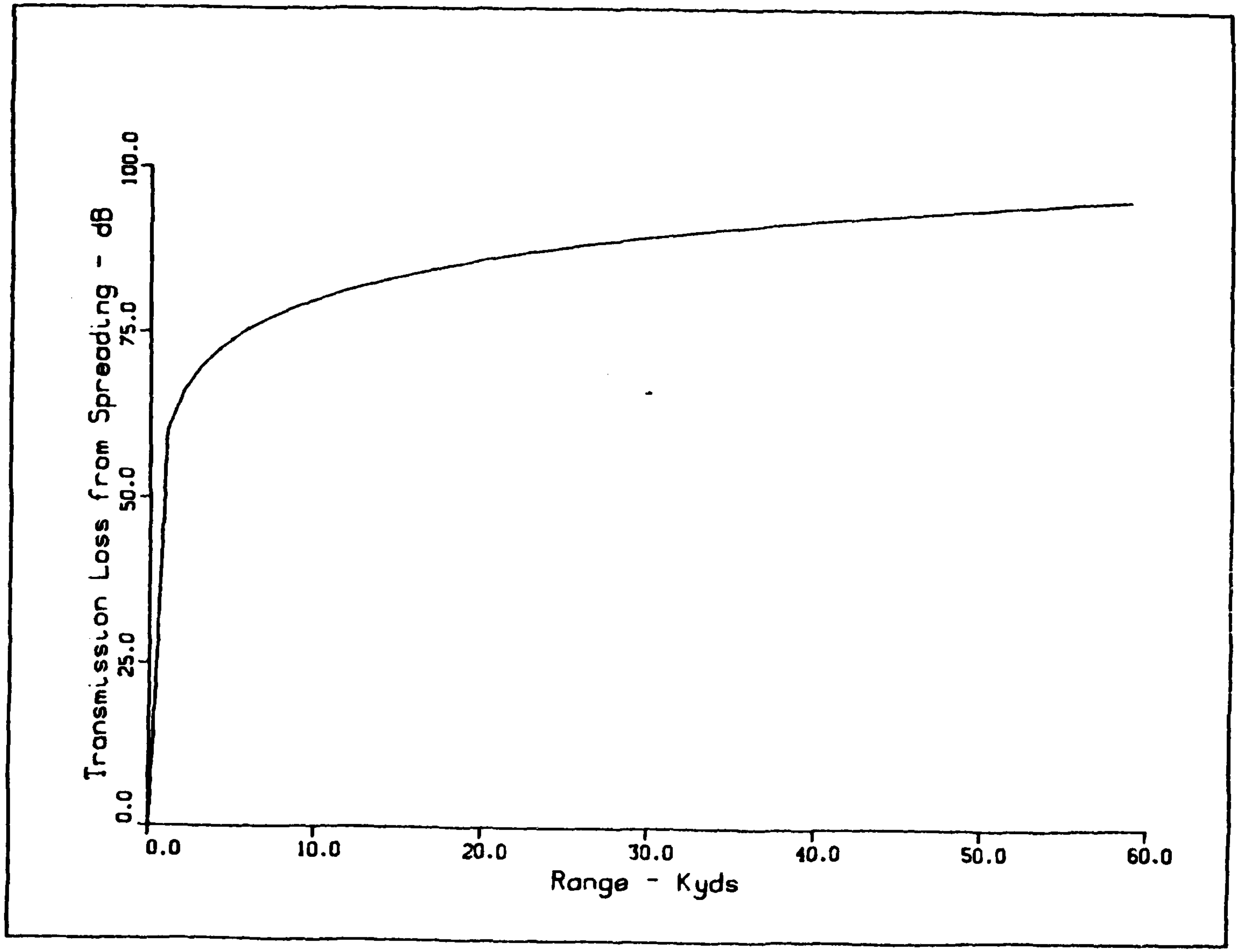

Figure 1. Spreading Loss Profile

losses is not an efficient use of available storage, so execution time calculation of this loss factor is recommended. Some execution time speed can be realized by pre-computing the parameter

$$b = 0.63*freq(1.4)^{(\text{sea state})} \qquad (4)$$

The sea state of a given area remains constant in a given area, so b can be precomputed for a number of frequencies and stored in a one-dimensional look-up table that is associated with an environmental area. Table 1 is an example of such a table using a sea state of 4.

2. Absorption Loss

To account for the additional transmission loss due to absorption of sound by the medium, an absorption loss factor should be included. The absorption loss corrections currently used in the NWCGS model is applied only to the active model. The correction used is of the form:

$$TL = TL + 0.033 * freq^{1.5} * \text{range (Kyd)} \qquad (5)$$

This equation, cited in Reference 2 is derived from research done by M.J. Sheehy and R. Halley [Ref. 3] in 1956. Their research attempted to determine the attenuation coefficient for low frequency sounds. The experiments involved detonation of a nuclear device several hundred miles off the coast of

TABLE 1

(sea state = 4)

freq	b	freq	b
1	2.42021	31	75.0264
2	4.84042	32	77.4467
3	7.26062	33	79.8669
4	9.68083	34	82.2871
5	12.101	35	84.7073
6	14.5212	36	87.1275
7	16.9415	37	89.5477
8	19.3617	38	91.9679
9	21.7819	39	94.3881
10	24.2021	40	96.8083
11	26.6223	41	99.2285
12	29.0425	42	101.649
13	31.4627	43	104.069
14	33.8829	44	106.489
15	36.3031	45	108.909
16	38.7233	46	111.33
17	41.1435	47	113.75
18	43.5637	48	116.17
19	45.984	49	118.59
20	48.4042	50	121.01
21	50.8244	51	123.431
22	53.2446	52	125.851
23	55.6648	53	128.271
24	58.085	54	130.691
25	60.5052	55	133.111
26	62.9254	56	135.532
27	65.3456	57	137.952
28	67.7658	58	140.372
29	70.186	59	142.792
30	72.6062	60	145.212

southern California, and recording the acoustic intensity of frequencies between 20 and 200 hertz. The data, collected from several locations in the eastern Pacific Ocean, was fitted using a least-squares regression technique to an approximating function described by equation (5). Extrapolating equation (5) to frequencies above 200 hertz and comparing the predicted results to measured data, their report concluded that equation (5) was a reasonable approximation for frequencies up to 60 Kilohertz.

Subsequent studies, cited by Urick [Ref. 4] have developed somewhat different approximating functions for the absorption coefficient. The most current of these is given by:

$$\alpha = 1.86 \times 10^{-2} \frac{SF_T f^2}{F_T^2 + f^2} + 2.86 \times 10^{-2} \frac{f^2}{F_T} \text{ dB/Kyd} \quad (6)$$

Figure 2 is a plot of absorption loss as a function of range. The two curves depicted are drawn using two approximating functions (equations 5 and 6). Figures 3 and 4 show how the choice of approximating function can affect the total absorption loss correction factor for a given range and frequency. It is evident from these plots that the differences between the two approximating functions are not large, however as the range or frequency increases, the difference between the two increases. Assuming that the approximating function cited by Urick is based on a larger set of experimental data,

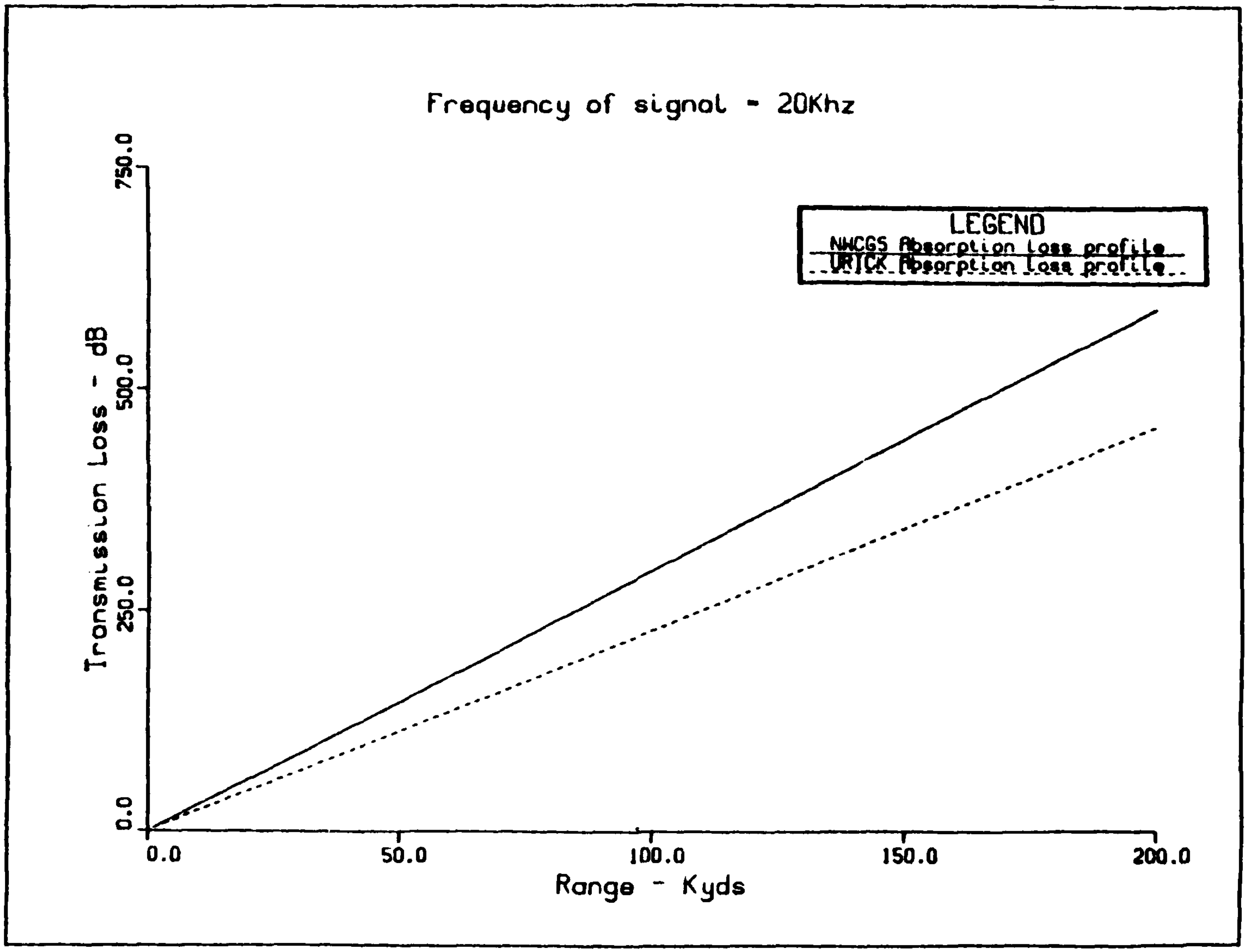

Figure 2. Absorption Loss Profiles

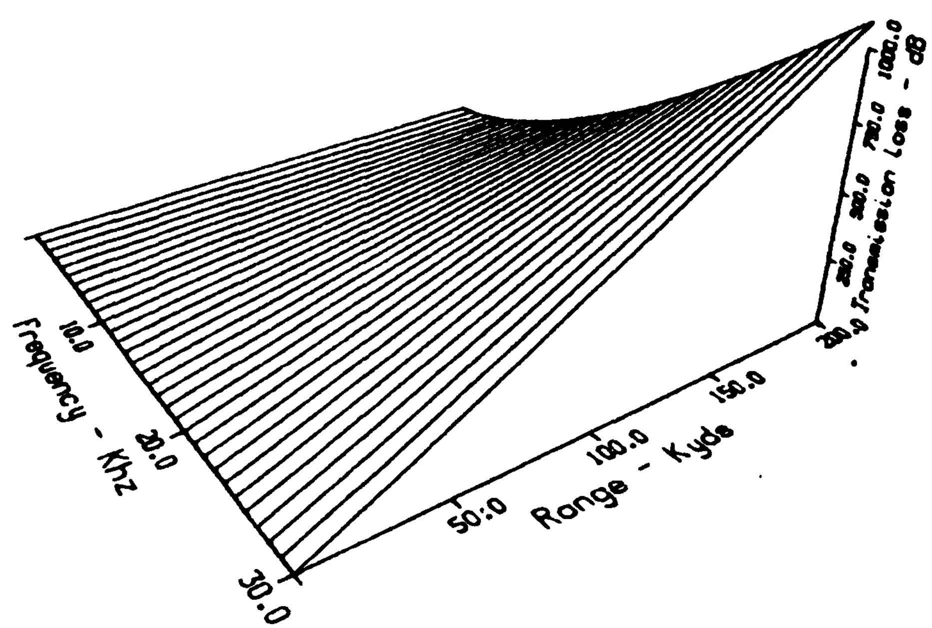

Figure 3. NWCGS Absorption Loss Characteristics Curve

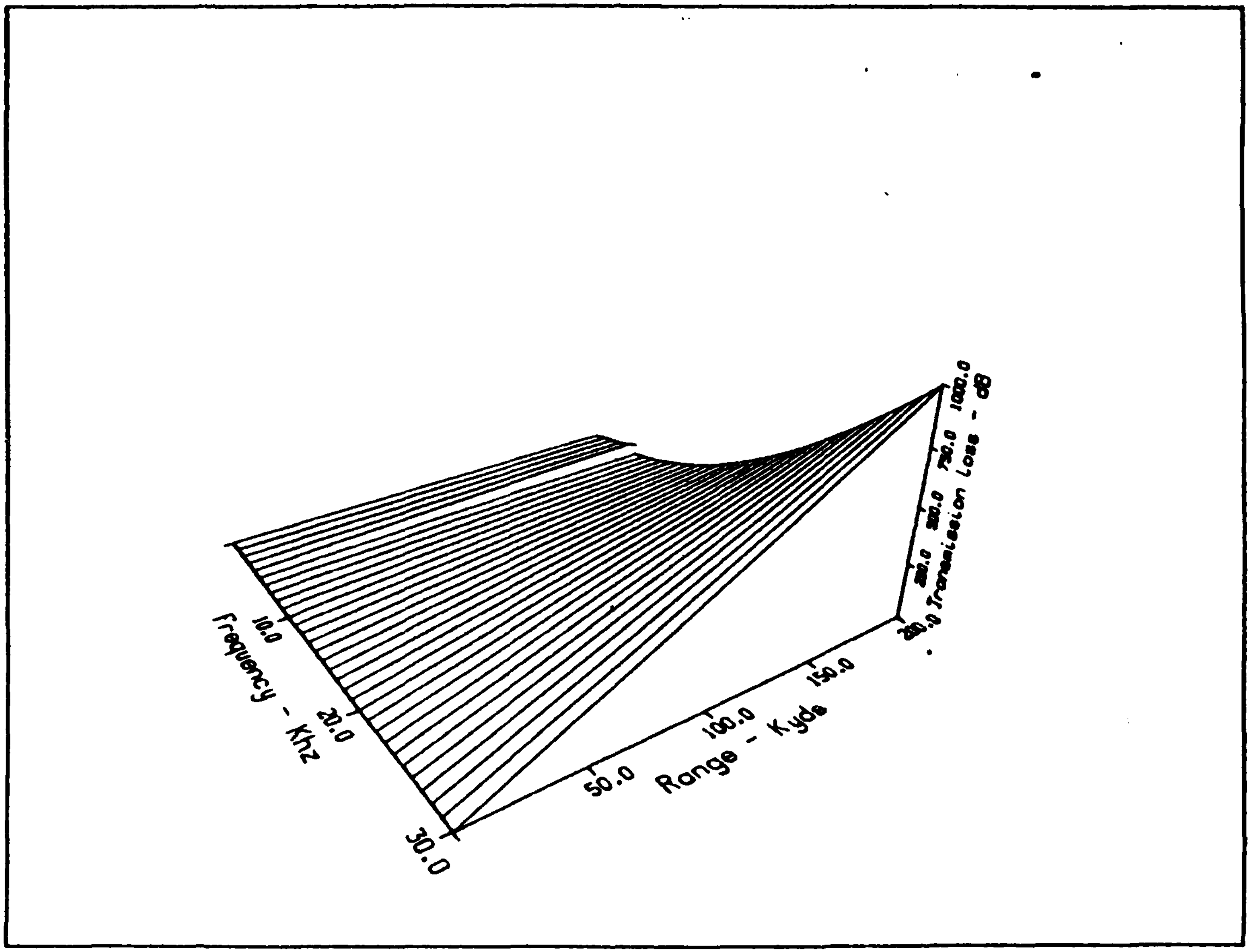

Figure 4. Urick's Absorption Loss Characteristics Curve

it is recommended that equation (6) replace equation (5) in the NWCGS detection modules. For the sake of consistency, it is further recommended that the absorption loss correction be applied to acoustic signals in the passive acoustic detection modules as well as the active acoustic detection modules. In the case of active detections, the frequency "f" of equation (6) is the ping frequency of the sonar transducer. In the case of passive detections, "f" should be the center frequency of the bandwidth in which the searcher is looking. Since equation (6) is a function of frequency alone, a one-dimensional absorption coefficient look-up table can be constructed. Table 2, derived from equation (6), provides data that may be useful in the construction of such a look-up table.

3. Convergence Zone Mode

If convergence zone transmission paths are possible, the NWCG system is able to adjust the transmission loss to reflect this type of contact. Whenever the searcher is in the target's convergence zone area, the NWCG system multiplies the unadjusted transmission loss by a convergence zone correction factor. In order to reduce the unadjusted transmission loss to reflect a convergence zone gain, the multiplicative factor must be a real number between zero and one. This method is significantly different than the method used by Coppens [Ref. 5] to describe this gain (see Appendix A). Since this method of adding rather than multiplying the

TABLE 2

(salinity = 35)
(temperature = 50 C)

freq	alpha	freq	alpha
1	.644164	31	15.0205
2	1.27433	32	15.378
3	1.89095	33	15.7298
4	2.49446	34	16.0758
5	3.08527	35	16.4163
6	3.66378	36	16.7514
7	4.23037	37	17.0813
8	4.7854	38	17.406
9	5.32922	39	17.7257
10	5.86218	40	18.0404
11	6.38459	41	18.3504
12	6.89676	42	18.6556
13	7.39899	43	18.9563
14	7.89157	44	19.2525
15	8.37477	45	19.5443
16	8.84886	46	19.8318
17	9.31409	47	20.1152
18	9.77072	48	20.3944
19	10.219	49	20.6696
20	10.6591	50	20.9409
21	11.0913	51	21.2083
22	11.5157	52	21.472
23	11.9327	53	21.732
24	12.3424	54	21.9884
25	12.7449	55	22.2413
26	13.1405	56	22.4907
27	13.5294	57	22.7367
28	13.9116	58	22.9794
29	14.2875	59	23.2188
30	14.657	60	23.4551

correction factor has become an accepted standard, it is recommended that the NWCG system be modified to take advantage of the availability of existing data bases.

4. Bottom Bounce Mode

Transmission loss is adjusted in the NWCG system whenever the environment supports bottom bounce. A bottom bounce flag is set if the range from target to searcher is within a bottom bounce region, and all transmission loss calculations are multiplied by a bottom bounce correction factor. The areas where bottom bounce detections are considered likely are those between the maximum direct path range and the minimum convergence zone range. While bottom bounce transmission paths can extend into both direct path and convergence zone areas, the transmission loss for bottom bounce is generally larger than that of the other two paths. Consequently, any detection that occurs in one of the other transmission areas will most likely not be due to bottom bounce. The current literature discussed in Appendix A describes the following procedure to adjust the transmission loss:

First, increase the effective range from target to searcher by the equation:

$$R = R/(\cos \theta) \tag{7}$$

where θ is the angle made between the incident sound wave and the bottom. The increase in range is due to the indirect

transmission path. Second, increase the total transmission loss by adding a constant factor BL due to absorption and scattering of the signal by the ocean bottom.

The spreading loss associated with bottom bounce transmission paths is spherical. Since the NWCGS spreading loss table describes cylindrical spreading, spreading loss values obtained from this table must be doubled to reflect that difference. The loss associated with a bottom reflection is an environmental parameter that should be included in the table that describes the environment.

An important aspect of bottom bounce often overlooked is its value in cases of layer depth interdiction. When the searcher is above the mixed layer, and the target is below that layer (or vice versa) direct path ranges are severely limited due to the refracting effects of the layer. Bottom bounce signals have much higher angles of incidence, and are therefore less affected by refraction. If layer depth interdiction occurs in bottom bounce areas, detections should be based strictly on bottom bounce transmission paths.

5. <u>Conclusion</u>

Figure 5 shows typical transmission loss profile for the three transmission modes (direct path, bottom bounce, and convergence zone). Using the equations of the NWCG system, a similar transmission loss profile has been computed and shown in Figure 6. The two figures are significantly different, especially in terms of bottom bounce transmission loss. A more extensive transmission loss look-up table is

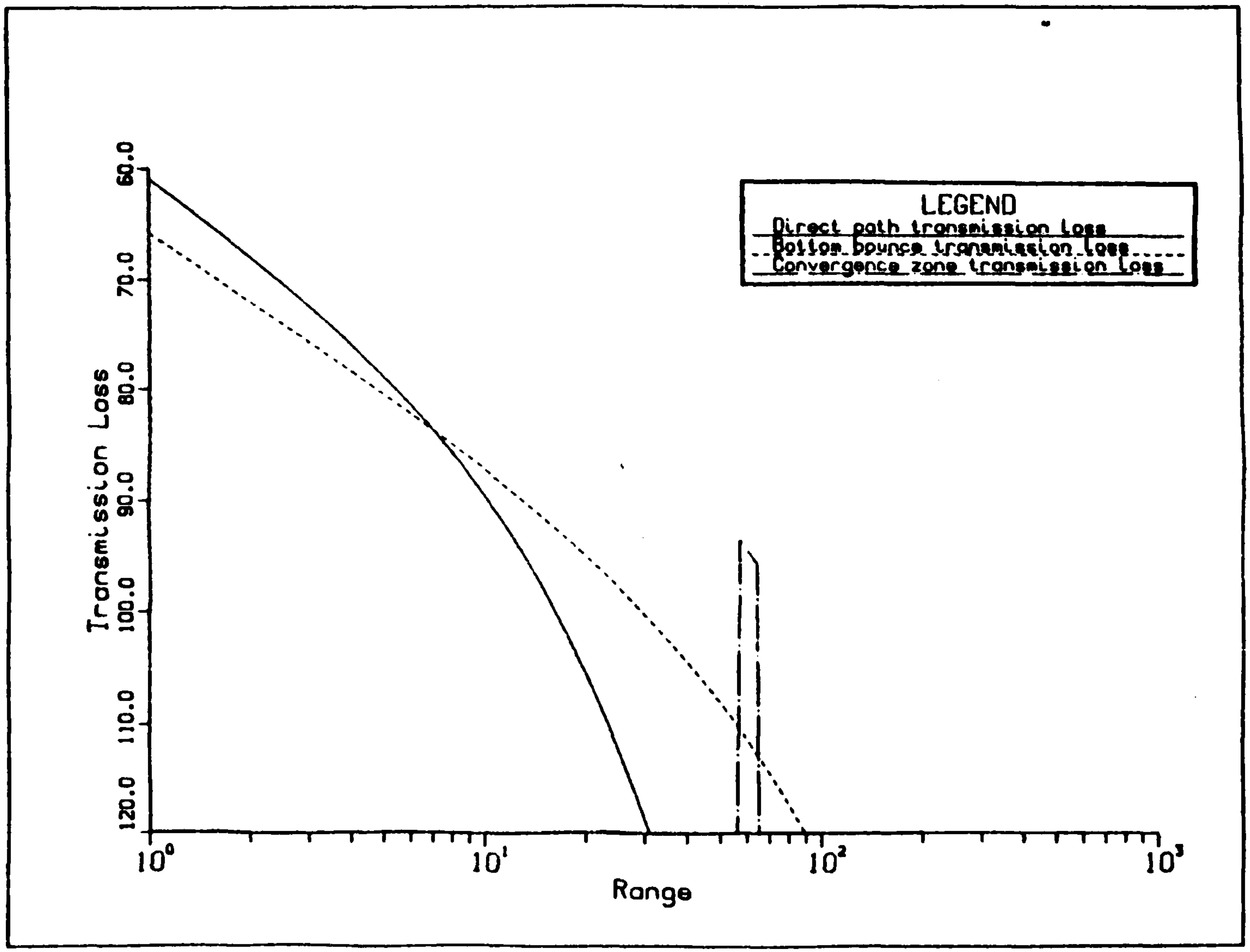

Figure 5. Transmission Loss Profile

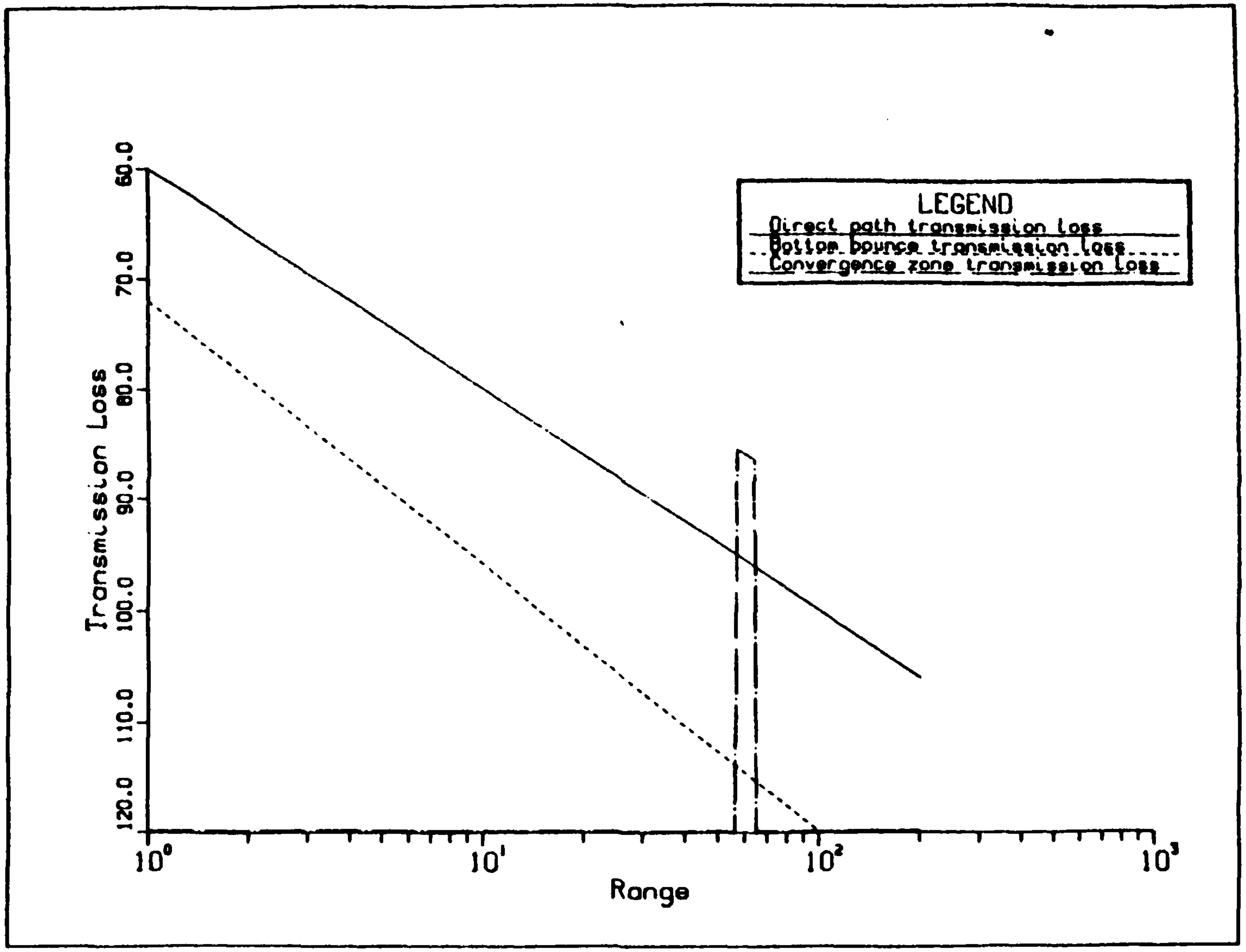

Figure 6. NWCGS Transmission Loss Profile

required to adequately describe spreading, absorption, transmission path, etc. This table could eliminate the need for bottom bounce and convergence zone correction factors, and could be used to describe environmental phenomena that are difficult to describe analytically. The NWCGS transmission loss look-up table could be modified to include frequency, in addition to environmental area and range, as an entering argument to the table. Additionally, the resolution of the table (currently 1000 yards) could be increased.

If the current structure of the transmission loss look-up table cannot be altered, the following recommendations are made:

1. Use the propagation loss table currently in the NWCG system to describe transmission loss due to cylindrical sreading only. Spreading losses are a function of range only, and the difference between cylindrical and spherical spreading losses is a multiplicative factor of two. All transmission paths are subject to spreading losses, and therefore all transmission paths will reference this table.
2. For direct path transmissions, transmission loss should be described by the equation:

$$TL = 10 \log r_t + 10 \log r + ar + br/r_r \qquad (8)$$

where:

$$r_t = 115 \text{ sqrt}(D_t^2/(D_t - D_{t1})$$

$$r_r = 918 \text{ sqrt}(D_t)$$

$$a = \text{absorption loss/yard}$$

$$b = \text{loss (dB)/reflection}$$

$$= 0.63*(1.4)^{(\text{sea state})} * (\text{freq})$$

The value r_t is fixed by the environment selected. Consequently, it is possible to compute the value of 10 log (r_t) beforehand, and include it in the parameter list of the environmental area. The value of 10 log (r) is obtained directly from the propagation loss look-up table. Absorption loss per yard "a" can be determined by a call to another look-up table (see Appendix A). The loss per bounce parameter "b" is a function of both sea state and frequency; and a two-dimensional look-up table similar to Table 2 can be constructed and used to determine "b".

3. For bottom bounce transmission paths, the transmission loss should be reflected by the equation:

$$TL = 20 \log (r/\cos \theta) + ar/\cos \theta + BB \qquad (9)$$

The range from target to searcher is divided by cos θ to account for the increased transmission path. The adjusted range is an entering argument for the propagation

loss look-up table. Since bottom bounce spreading is spherical rather than cylindrical, the value obtained from the table should be doubled. Absorption coefficient "a" is the same as previously described, and the bottom bounce loss BB is a parameter determined by the environmental area.

4. In areas wihtout bottom bounce, if the detector is above the mixed layer and the target is below (or vice versa), it is reasonable to assume no detections are possible. Under the same circumstances in a bottom bounce area, detections via bottom bounce transmission paths are possible, and should be investigated. This would require the modification of the layer depth interdiction test. If the detector is above the layer and the target is below (or vice versa) and the bottom bounce available flag is not set, then no detection can occur. If the bottom bounce available flag is set, transmission loss is calculated for bottom bounce mode.

C. THRESHOLD CROSSING MODELS

A major use of the passive or active sonar equation is to determine mean signal excess. Mean signal excess is the average difference (in decibels) between the measured signal-to-noise ratio and the signal-to-noise ratio which will yield a 50 percent probability of detection for a specified probability of false alarm. The NWCGS utilizes a signal excess

threshold crossing model to account for the randomness in the components of the sonar equation, and to determine the probability of detection. This model defines the signal excess at a time t to be a random variable $X_{SE}(t)$ and a detection to be the event $\{X_{SE}(t) \geq 0\}$. The signal excess at time t can be expressed as:

$$X_{SE}(t) = SE(t) + X(t) \tag{11}$$

where SE(t) is the mean signal excess, and X(t) is a random variable that determines the variability of the signal excess at time t. Values for X(t) are determined by drawing from a normal distribution having a mean of zero, and a variance that is determined by the variability of the components of the sonar equation. The probability that a detection will occur can be written as follows:

$$P\{X_{SE}(t) \geq 0\} = P\{X(t) \geq -SE(t)\} \tag{12}$$

Since X(t) is normally distributed, this implies that

$$P\{X_{SE}(t) \geq 0\} = \Phi\{SE(t)/\sigma\} \tag{13}$$

The mean signal excess is used as an entering argument for an inverse normal look-up table that determines the probability of detection.

Two modes are available for converting the detection probability into a detection decision, the deterministic mode and the probabilistic mode. In the deterministic mode, the probability of detection is compared to a probability of detection threshold that has been set by the umpire during the initialization of the game. If the computed probability of detection exceeds this predetermined threshold, a detection is recorded. The alternative to the deterministic mode is the probabilistic mode. In this case, the probability of detection is computed, and the detection process is simulated by a draw from a Uniform (0,1) distribution. A detection occurs whenever the random variable drawn is less than the computed probability of detection.

When using the deterministic mode with a given standard deviation σ, the probability of detection threshold initialized by the game director defines a signal excess to sigma ratio threshold $(SE/\sigma)_{TH}$ by:

$$\Phi(SE/\sigma)_{TH} = (Pd)_{TH} \tag{14}$$

If the probability of detection threshold is initialized to 0.5, then $(SE/\sigma)_{TH} = 0$ and a detection occurs anytime the mean signal excess is equal to or greater than zero. In the probabilistic mode, the value $\Phi\{SE/\sigma\}$ is compared to a random draw. If $\sigma \to 0$, then for any non-negative value of SE, $\Phi\{SE/\sigma\} \to 1$, and detections occur with probability 1. For

any negative value of SE, $\Phi\{SE/\sigma\} \rightarrow 0$, and detections occur with probability 0. Consequently, in the limiting case where $\sigma = 0$, detections occur whenever the mean signal excess is equal to or greater than zero, and in this limit, the probabilistic mode is equivalent to the deterministic mode with the probability of detection threshold set to 0.5. This suggests that the deterministic mode can be replaced by this limiting form of the probabilistic mode unless there is some utility in having $(Pd)_{TH}$ set to a value different from 0.5.

The probabilistic mode corresponds to a complete independence model. In this mode, detection on a look is independent of detection on any other look. The cumulative probability of detecting a target in N looks is given by:

$$P\{\text{detecting in N looks}\} = 1 - \prod_{i=1}^{N} \{1 - Pd(i)\}^{i} \qquad (15)$$

where PD(i) is the detection probability on the i^{th} look. For any non-zero probability of detection Pd, the cumulative probability of detection approaches one as the number of looks increase. Figure 7 shows the cumulative probability of detection for a complete independence model as a function of the number of looks, where the mean signal excess is constant and the single look probability of detection is 0.1.

This figure also indicates the sensitivity of this model to the time between looks. It shows that after 22 looks,

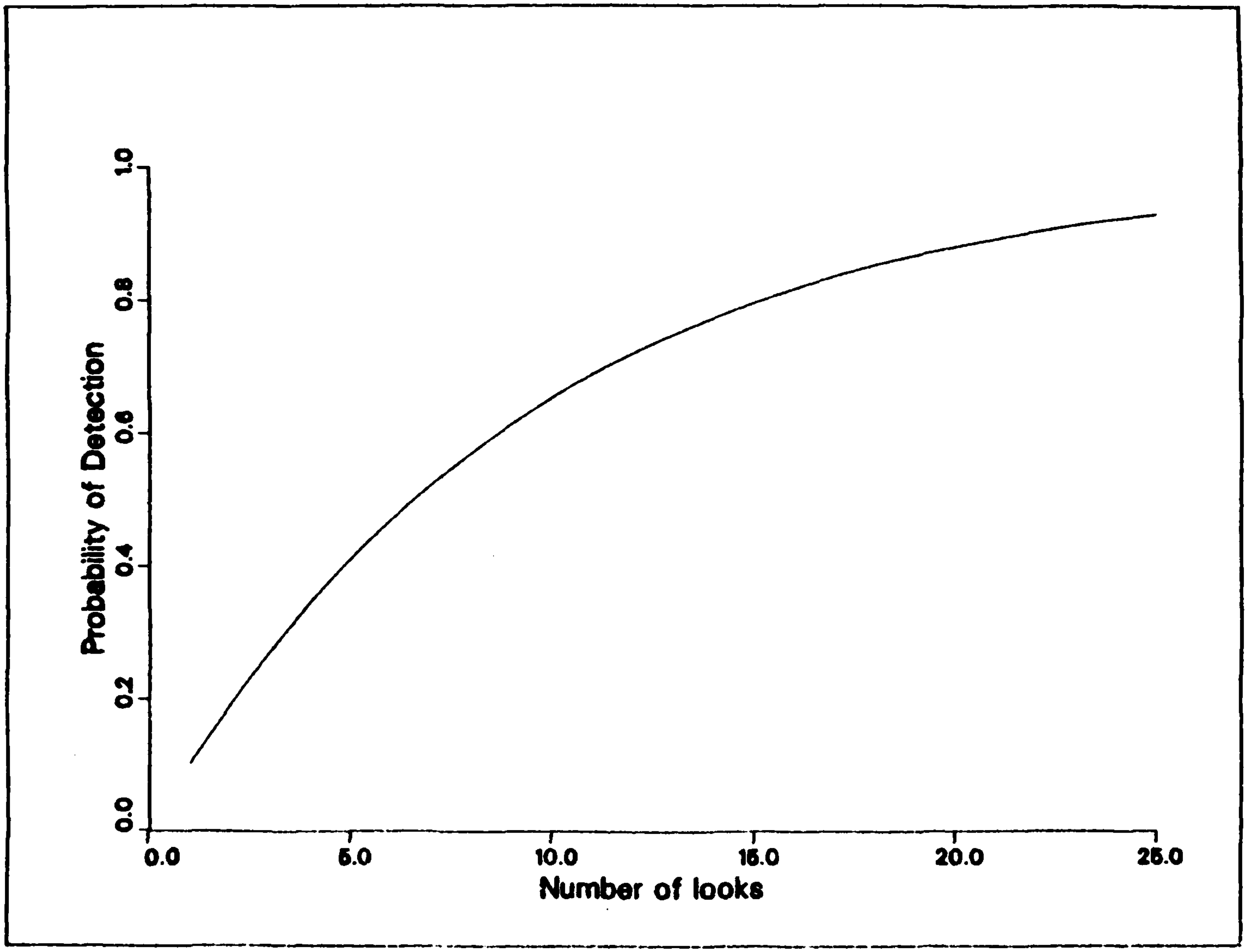

Figure 7. Cumulative Probability of Detection Complete Independence Model

the cumulative probability of detection exceeds 90 percent. It can also be shown that the average number of looks to a detection is 10. For this model to be valid, the time between looks must be long enough to have the independence assumption hold. In the case of passive acoustic detections, the time between looks must also be long enough to satisfy the integration time requirements for detection threshold. In the NWCGS, the time between looks is a director adjustable parameter initialized to 20 minutes. It is important that the game director understand how changing this value affects the cumulative probability of detection. The discussion which follows describes some alternative models.

1. <u>(λ-σ) Jump Model</u>

A more complicated model for the random component of signal excess than the one used in the NWCGS was introduced by J.D. Kettelle in 1960. It is referred to as the (λ-σ) jump model. In this model, the initial value of X(t) is determined in the same manner as that used in the NWCGS model; that is by a draw from a normal distribution having a mean of zero and a standard deviation of σ. On subsequent looks, the value of X(t) remains the same until a jump occurs. The time of the jump is determined by a draw from an exponential distribution having a mean of λ. Each time a jump occurs, a new value for X(t) and a time to the next jump are determined. The choice of lamda (known as the inverse relaxation constant) determines the model's level of dependence. As

$\lambda \to \infty$, the mean time between jumps approaches zero, and the model approaches the independence model. As $\lambda \to 0$, the time between jumps approaches ∞, and this limiting case corresponds to a complete dependence model. Complete dependence refers to the fact that if a detection does not occur on the detection opportunity, or "look" with the largest mean signal excess, then detection will not occur on any other look. Therefore, the cumulative probability of detection for a series of looks is equal to the probability of detection for the look with the largest mean signal excess. Figure 8 shows a number of possible cumulative probability of detection curves available for a given mean probability of detection (0.1) and different values for λ.

2. Gauss-Markov Models

An alternative to the (λ-σ) jump model is the Gauss-Markov model. This model is Gaussian in nature because the joint distribution of a set of looks [X(1),X(2),...,X(n)] is a multivariate normal distribution. For any X(i), its marginal distribution is normal with a mean of zero, and a variance of σ^2. It is Markovian, implying that given values for X(0), X(1), ..., X(t-1), the value of X(t) depends only upon X(t-1). This conditional dependence of X(t) on X(t-1) is normally distributed with a mean of ρ*X(t-1), and a variance of $\sigma^2 * (1-\rho^2)$. The parameter ρ, known as the autocorrelation coefficient, is defined by the equation:

$$\rho = e^{-\lambda t} \qquad (15)$$

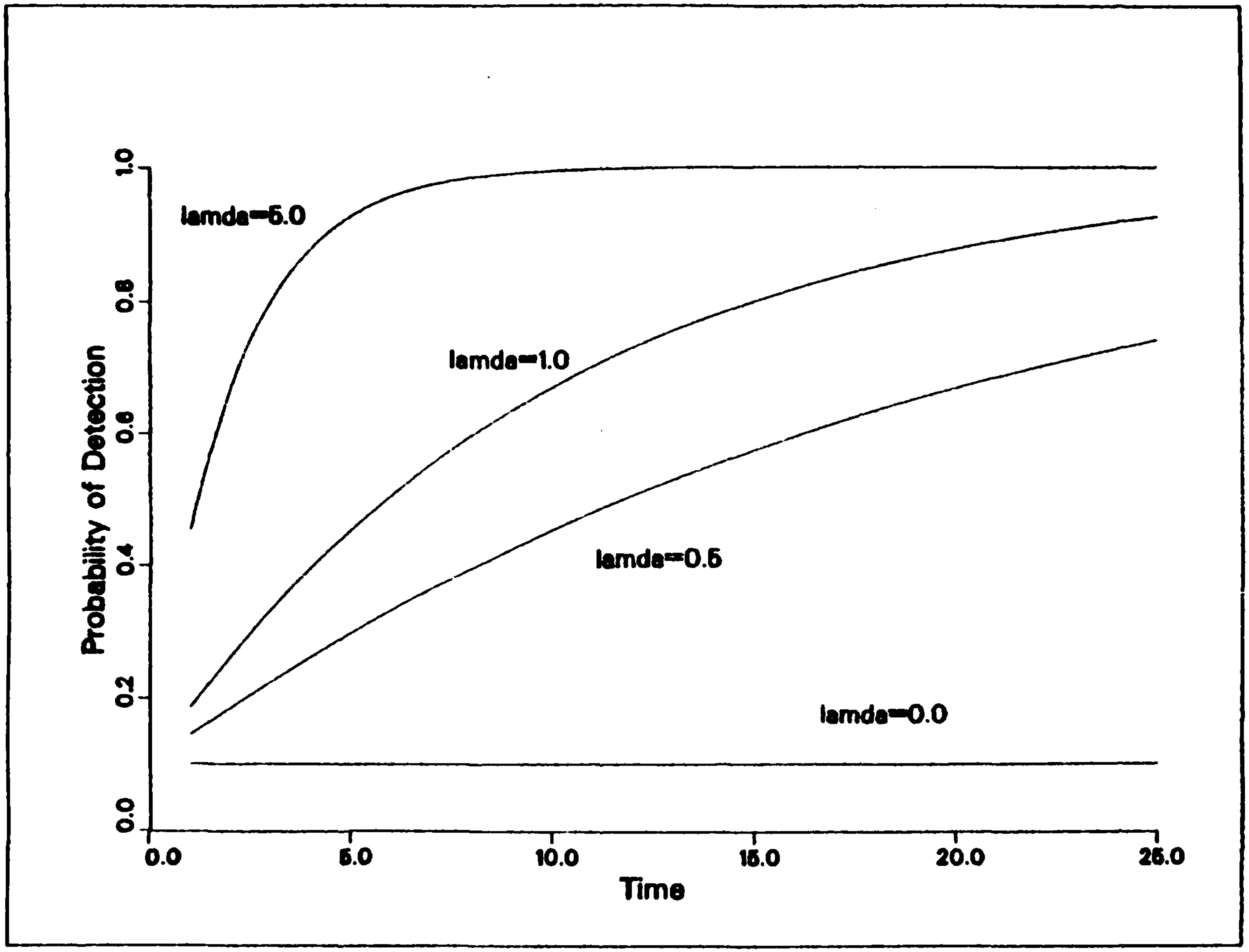

Figure 8. Cumulative Probability of Detection Curves--Lamda-Sigma Jump Model

The parameter λ of equation (15) corresponds to the inverse relaxation coefficient of the (λ-σ) model. As $\lambda \to 0$, the value of $\rho \to 1$ and, as with the (λ-σ) model, the Gauss-Markov model approaches a complete dependence model. Similarly, as $\lambda \to \infty$, the value of $\rho \to 0$ and the Gauss-Markov model approaches the independence model. The degree of dependence is determined by choice of λ.

Although the Gauss-Markov model is difficult to deal with analytically, a computer model that uses the conditional distribution of X(t) given X(t-1) is not difficult to develop. Cumulative probability of detection curves derived through simulation using various values of lamda are presented in Figure 9.

3. K Out of N Models

The k out of N detection model that is described here is based on independence model, however, each look results in either a success or failure rather than a detection or a non-detection. For a detection to occur, k successes must have occurred within the last N looks. Such models provide a means of describing operator characteristics. Figure 10 shows how the k out of N model compares with the dependence and independence models of the NWCGS. The k out of N model offers the advantage of allowing one to set the time between looks to any specified time interval and then, by choice of k and N, of fitting the model to an appropriate cumulative probability of detection curve. Most detection processes

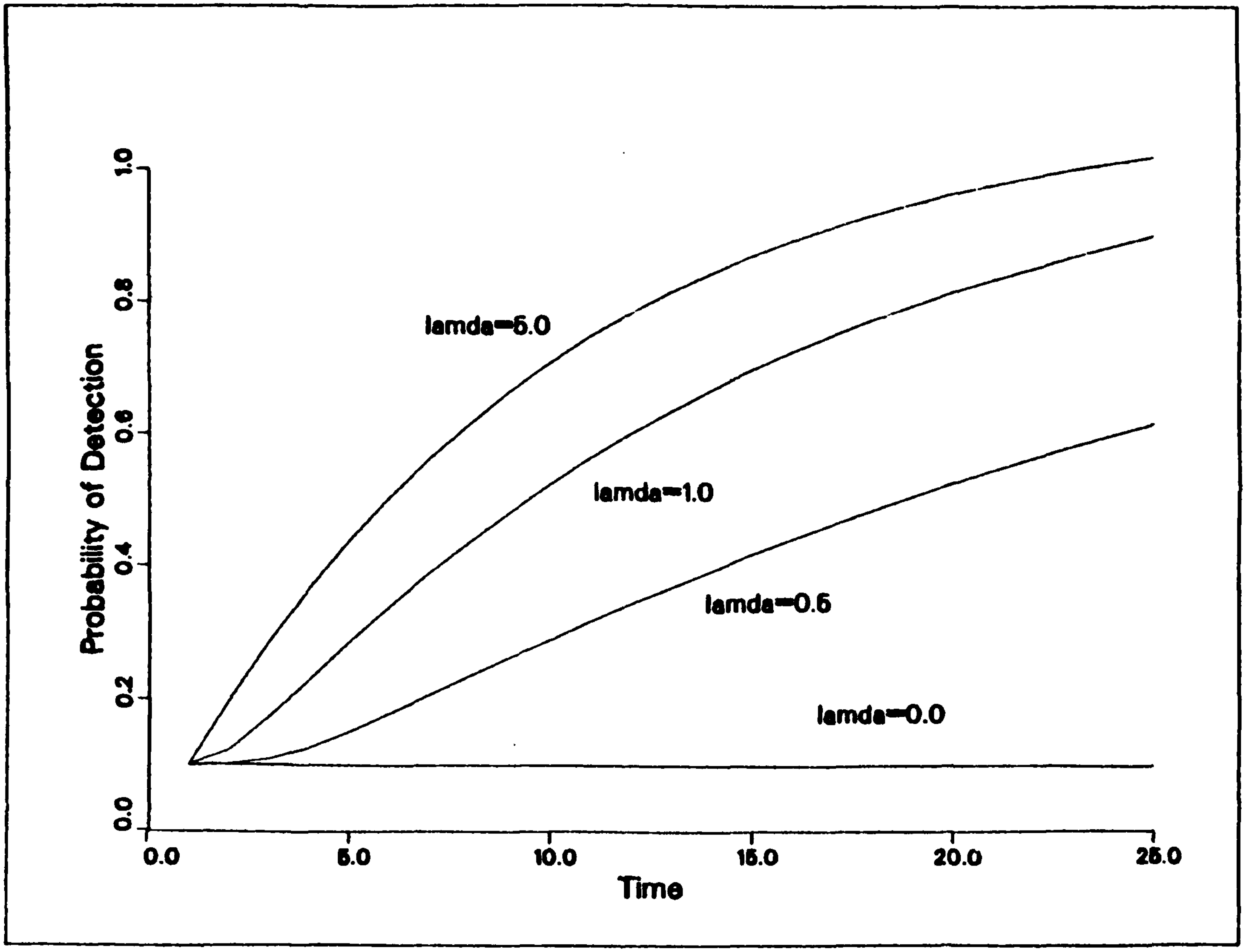

Figure 9. Cumulative Probability of Detection Curves--Gauss-Markov Models

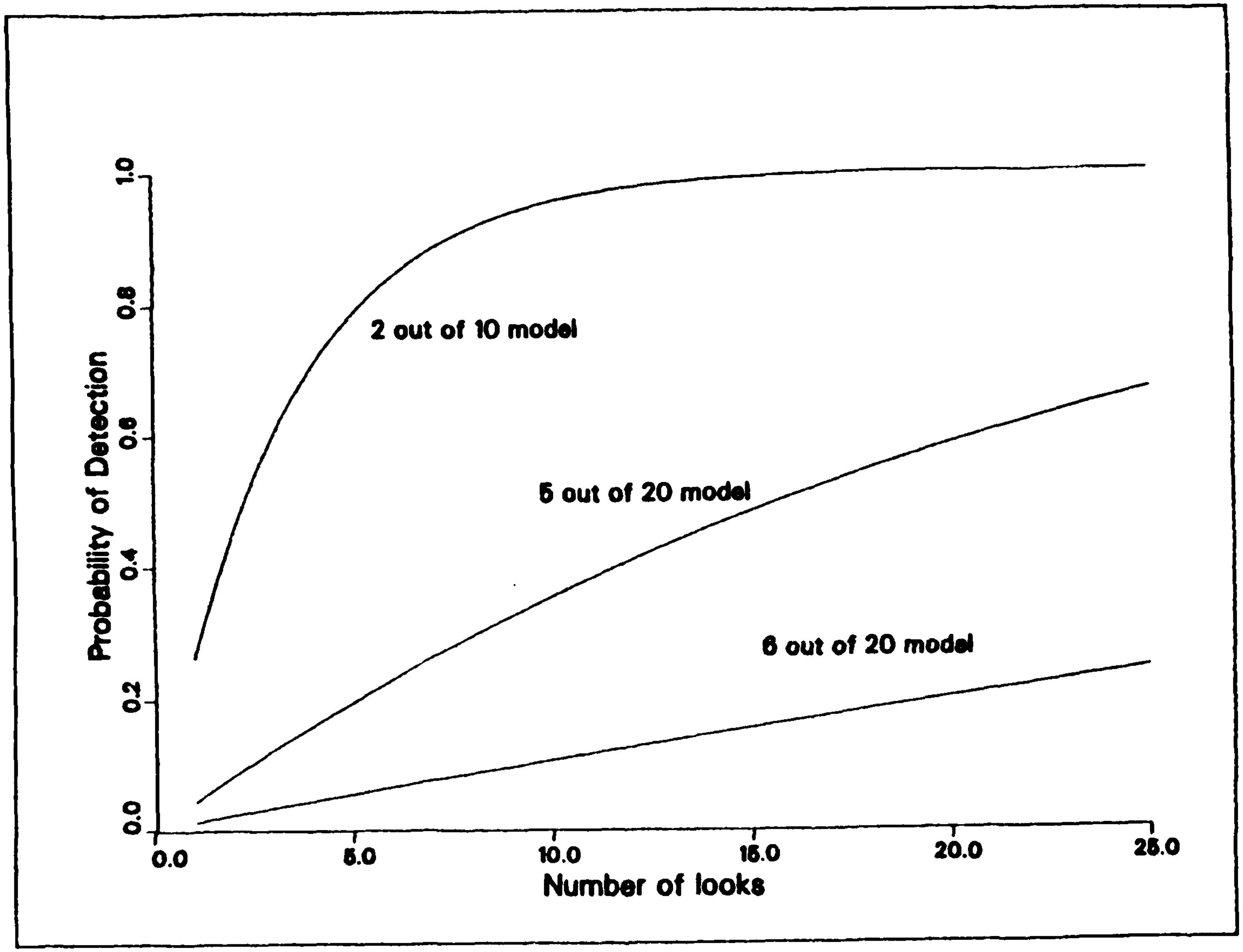

Figure 10. Cumulative Probability of Detection Curves--k Out of N Models

require an initial integration time before a detection can be called, and this model can easily accommodate such a phenomenon. A k out of N model could also have been based on either the (λ-σ) jump model or the Gauss-Markov model.

An example of a more general k out of N model can be found in the APSURF Surface Ship Engagement Model [Ref. 6]. In that model, active sonars were modelled as follows:

1. A 6 out of 28 model determined detections if the operator was unalerted.
2. A 5 out of 20 model determined detections if the operator was alerted.
3. A 2 out of 10 model was used after a detection to determine if contact was still being maintained.

This model is easily implemented and would require very little in the way of software modification to the existing NWCGS model.

4. <u>Summary</u>

The alternative models described above are a sample of the models that have been used to describe the detection process. Although none of the models are without shortcomings, each of them has desirable properties not found in the current NWCGS models. In particular, they provide a range of serial correlation properties. This is appealing in modeling a detection process where the probability of detection time t may be influenced by information obtained at earlier times.

APPENDIX A

The most effective mechanism for locating targets under the ocean surface is the detection and evaluation of acoustic information specific to a target of interest. With this mechanism, detection may occur as a result of passively listening to the sounds generated by the target's propulsion equipment and auxiliaries, or may involve actively radiating acoustic energy in the suspected direction of the target and listening for the echo which would reflect off the target and return to the searcher. Passive sonar systems offer the advantage of being able to detect noisy targets at extremely long ranges (often in excess of one hundred miles) without alerting the target to the search. Although active sonar systems, or echo ranging systems, alert the target to what the searcher is about, they can be most effective against a quiet, slow-moving target close to the searcher. The system of choice is determined by the tactical situation and the environmental conditions under consideration.

The passive acoustic modules used in the NWCGS are based on the generalized expected value sonar equations first formulated during the Second World War. Signal Excess, or the difference between the existing signal-to-noise ratio and that required to achieve a specified level of performance [Ref. 7] is the fundamental parameter that determines whether or not a detection has occurred in these modules. The required

signal-to-noise ratio (in decibels) is called the detection threshold. It is defined to be the signal-to-noise ratio that will give a specified probability of detection for a specified false alarm probability in a forced choice decision situation. If the specified probability of detection is equal to 0.5, detection threshold is usually referred to as recognition differential.

After determining the appropriate detection threshold, the detection model determines the current signal excess level using the formula

$$SE = SL - TL - NL + DI - DT \qquad (A1)$$

for modeling passive detections, and

$$SE = SL - 2TL + TS - NL + DI - DT \qquad (A2)$$

for modeling active detections, where the parameters of the equations are defined as:

SE - Signal Excess

SL - The source level of the target as measured one yard from the acoustic center of the source

DI - The directivity index of the receiver

TL - The one-way transmission loss from the target to the source

NL - The non-target noise existing in the area of the receiver

TS - The target strength as measured one yard from the acoustic center of the target

DT - The detection threshold, or the minimum signal-to-noise ratio (in decibels) that is required to call a detection

A more detailed discussion of these parameters follows.

A. SOURCE LEVEL

The value of the acoustic energy radiated into the medium by the searcher is termed the projector source level. For the sake of standardization, the source level is taken to be the acoustic power as extrapolated back to one yard from the acoustic center of the sound source. The interference patterns and other physical characteristics of acoustic energy close to its source produce measurements which are of little value, so in practice the acoustic measurements are made from large distances, and the results can be reliably extrapolated to give reasonable source levels for all meaningful ranges. In passive acoustic listening, the signals of interest are those which are generated by the target alone.

B. DIRECTIVITY INDEX

Total acoustic power arriving at the receiving unit (be it a single hydrophone or array of hydrophones) consists of both signal power and noise power. Signal power is generally assumed to arrive at the receiver from a signal direction. Conversely, noise power is generally assumed to arrive at

the receiver uniformly from all directions. A receiving unit that only accepts acoustic power from specific directions usually has a higher signal-to-noise ratio than a receiving unit that accepts acoustic power omni-directionally. The signal-to-noise ratio gain due to the directivity of the receiving unit is termed the directivity index DI of the receiver.

C. TRANSMISSION LOSS

As with any other form of radiated energy, acoustic signals are subjected to a number of physical effects which tend to distort and dissipate the signal. In the acoustic sonar models, these effects are collectively described by the parameter transmission loss (TL). The primary constituents of transmission loss are spreading, and absorption.

An omni-directional sound source in a lossless infinite medium will radiate the same acoustic power over an ever-increasing area. Acoustic intensity, the quantity being measured by a detection system, is equal to power "P" divided by the total area "A" over which the intensity is distributed:

$$P = I * A \tag{A5}$$

If acoustic energy is subject only to spherical spreading in a lossless medium, the transmission loss can be described by:

$$TL_s = 20 \text{ LOG } (r) \tag{A6}$$

where r is the radius from the center of the sound source. In this case, intensity is inversely proportional to the square of the distance between detector and the center of the sound source.

When physical or environmental boundaries serve to inhibit spherical spreading by restricting sound between two parallel planes (the ocean floor and surface as an example), the power is radiated more like a cylinder of constant height "h" and increasing radius "r". The area of this cylindrical acoustic wave would be:

$$A = 2*\pi*r^2*h \tag{A7}$$

Intensity is inversely proportional to the first power of range making the spreading loss component of transmission loss equal to

$$TL_s = 10 * LOG(r) \tag{A8}$$

Initially, the intensity of sound sources spreads spherically. At some distance r_t away from the sound source, the acoustic intensity fills the medium between its bounds and spreading losses become more cylindrical than spherical. If the searcher is further away than this transition range, the transmission loss equation can be described by

$$TL = 10 * (LOG (R_t) + 10 * LOG (r) \tag{A9}$$

The most common instance of this type phenomena both the target and the searcher are in the surface layer where the sound velocity profile is such that a lower acoustic "boundary" is formed. A similar, though less common example is the SOFAR, or deep sound channel formed when the target and searcher detection system are both located in a channel where sound is trapped from above and below by acoustic "boundaries" [Ref. 8]. In either event, the threshold range R_t is related to the height of the channel D_1 and depth of target below the top of the channel D_t by

$$R_t = 1.094 * \mathrm{sqrt}\ (D_1^2/(D_1 - D_t)) \qquad \text{(A10)}$$

where all quantities are measured in yards.

1. Convergence Zone

The nature of the oceans are such that given sufficient depth, all acoustic signals will be refracted back toward the surface. In this refraction process, the sound waves tend to converge, thereby reducing the losses due to spreading. These convergence rings, or zones as they are called, have transmission losses at least 10 dB less than they would be if the transmission were only spherical spreading. To account for this, transmission losses are calculated, and a convergence zone gain parameter CZ is subtracted from the expected transmission loss.

2. Bottom Bounce

The mud-sand composition of much of the ocean floor tends to absorb rather than reflect acoustic signals. If the bottom consists more of rocks and sand than mud, the reflective properties of those materials will allow transmission of sound at greater than anticipated ranges. To account for this effect, a bottom bounce adjustment factor BB can be subtracted from the transmission loss calculation.

3. Absorption Losses

After spreading losses, the second greatest cause of intensity dissipation is absorption. This is caused by the conversion of acoustic energy into another form of energy. This type loss is usually attributed to shear viscosity, a friction-like conversion of acoustic energy into heat, or to energy involved in the dissociation and reassociation of ions in the ocean. The shear viscosity is associated with all frequencies of sound, while the dissociation reassociation phenomena predominate at frequencies below 100 kHz. The intensity if absorbed exponentially with distance travelled through the absorbing medium and transmission losses associated with absorption can be described by:

$$TL_a = \alpha r \qquad \text{(A11)}$$

where α is the absorption coefficient of the medium in units of decibels per kiloyard. A number of studies have been done in an effort to define an appropriate value for alpha.

It has been shown that the [Ref. 9] absorption coefficient is primarily a function of frequency and can be approximated using the equation:

$$\alpha = 1.86 \times 10^{-2} \frac{SF_T f^2}{F_T^2 + f^2} + 2.86 \times 10^{-2} \frac{f^2}{F_T} \quad \text{dB/Kyd} \qquad \text{(A12)}$$

where f is the frequency of the sound, S is the salinity (in parts per thousand) of the sea, and F_T is a relaxation frequency related to temperature T by the equation:

$$F_T = 21.9 * 10^{(6-[1520/(T+273)])} \qquad \text{(A13)}$$

Additional causes of transmission losses are absorption of sound into the ocean floor, scattering of sound energy at the surface, leakage of sound energy out of a sound channel, changes in the absorption coefficient due to depth and temperature changes, etc. A complete accounting for all the elements which comprise transmission losses would be computationally impractical and unnecessary for the model being discussed. As a minimum however, losses due to spreading and absorption should be considered.

Transmission loss models are primarily a function of frequency of the sound source, and distance from the source to the target. As such, the one-way transmission loss from target to detector will be the same for active and passive sonars (assuming both systems are using the same frequency).

Active sonar signals must travel from source to target and back, so the transmission loss in that circumstance is assumed to be exactly twice that of a passive sonar signal.

D. NOISE LEVEL

Any sound not originating from the target of interest is considered to be noise in the sonar model. Noise levels are generally categorized as either ambient noise (AN) or searcher self-noise (SN).

Ambient noise is the inherent noise of the ocean itself. It is a collection of acoustic signals emanating from numerous sound sources randomly arriving at the location of the searcher's hydrophone. It is primarily a result of the following factors:

1. Environmental effects--tidal activity, rain, wind, seismic activity, turbulence, sea state, etc.
2. Biologics--whales, dolphins, snapping shrimp, croakers, etc.
3. Man-made effects--shipping intensity, petroleum exploration, deep water mining, etc.

The diversity of sound sources involved in the makeup of ambient noise means that the entire acoustic spectrum is affected. It also implies that ambient noise is likely to be one of the most variable factors in the sonar equation. Ambient noise is usually modeled as a normal random variable whose mean is dependent upon the shipping intensity in the area of the searcher and target [Ref. 10].

Another major contributor to the undesirable noise at the detector is the self noise of the searcher. Auxiliary equipment is always being operated, and propulsion equipment is nearly always in use. As the speed of the searcher increases, so does the self noise problem associated with the propulsion equipment. At higher speed, the turbulence created by water flowing around the hydrophones becomes an additional source of self noise. Hydrophones are generally placed well forward of machinery spaces and have designed directivity away from any self noise sources, however total elimination of self noise is impossible. Self noise is usually modeled as a function of the speed of the searcher.

E. TARGET STRENGTH

When a target is ensonified by an active detection system, a portion of the incoming power is reflected back to the searcher. If the target were a perfectly reflecting spherical body, the sound energy would be reflected uniformly about the target, spreading spherically. In practice, targets are neither spherical, nor perfectly reflective. Target strength (TS) is the parameter that accounts for both absorption of energy by the target, and its reflectivity in the direction of the searcher. Target strength is strongly influenced by the relative angle of the target and searcher (aspect angle). The variance of target strength with aspect differs widely among targets, but as a first order approximation, Urick [Ref. 11] proposed an average submarine

target strength to aspect relationships which can be described by the equation:

$$TS = TS_o * (16.17 - 2.98 \cos(2\beta) - 3.083 \cos(6\beta) \qquad (A14)$$

where TS_o is the maximum value of target strength, and β is the aspect angle between target and searcher. Figure 11 shows how this equation relates target strength to aspect angle.

F. DETECTION THRESHOLD

Target information available to the searcher is processed in some manner to arrive at a detection decision. The signal excess models used in the NWCGS assume that detections occur whenever the signal-to-noise ratio (in decibels) exceeds some predetermined detection threshold DT. The choice of DT determines the probability of making a decision error. In a situation where a system is forced to make a decision after a single look, a detection will be called if the input exceeds a threshold. When no target is present, the input is due to noise alone. In this event, if the input level exceeds the threshold, a detection will be erroneously called, and a decision error known as false alarm occurs. When a target is present, the input level is both signal and noise. In this event, if the combined signal and noise input level exceeds the threshold, the system will correctly decide that

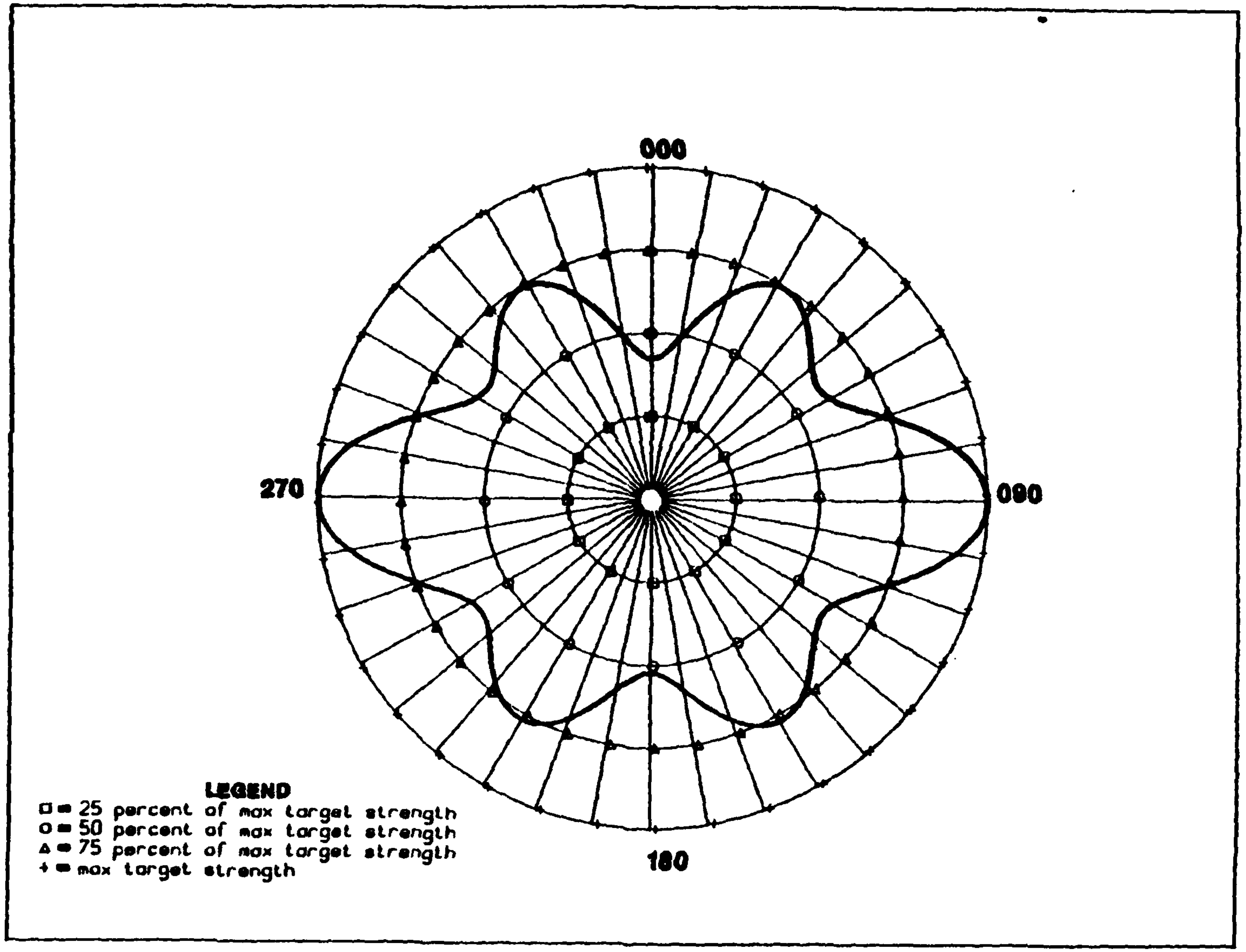

Figure 11. Aspect Effect on Target Strength

a target exists. Specifying the acceptable probability of false alarm determines a threshold. Having established a threshold, a specified probability of detection determines a required signal-to-noise ratio. This signal-to-noise ratio (in decibels) is the detection threshold DT.

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